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EXPRESS LETTER

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# Evaluation of GOCE-based global gravity field models over Japan after the full mission using free-air gravity anomalies and geoid undulations

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**Abstract**

The performance of Gravity field and steady-state Ocean Circulation Explorer (GOCE) global gravity field models (GGMs), at the end of GOCE mission covering 42 months, is evaluated using geoid undulations and free-air gravity anomalies over Japan, including six sub-regions (Hokkaido, north Honshu, central Honshu, west Honshu, Shikoku and Kyushu). Seventeen GOCE-based GGMs are evaluated and compared with EGM2008. The evaluations are carried out at 150, 180, 210, 240 and 270 spherical harmonics degrees. Results show that EGM2008 performs better than GOCE and related GGMs in Japan and three sub-regions (Hokkaido, central Honshu and Kyushu). However, GOCE and related GGMs perform better than EGM2008 in north Honshu, west Honshu and Shikoku up to degree 240. This means that GOCE data can improve geoid model over half of Japan. The improvement is only evident between degrees 150 and 240 beyond which EGM2008 performs better than GOCE GGMs in all the six regions. In general, the latest GOCE GGMs (releases 4 and 5) perform better than the earlier GOCE GGMs (releases 1, 2 and 3), indicating the contribution of data collected by GOCE in the last months before the mission ended on 11 November 2013. The results indicate that a more accurate geoid model over Japan is achievable, based on a combination of GOCE, EGM2008 and terrestrial gravity data sets.

**Keywords:** Geoid model, Gravity, GPS/levelling, GOCE, EGM2008

## Background

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission was launched on 17 March 2009 from the Plesetsk Cosmodrome in Russia by the European Space Agency (ESA). The GOCE mission finally ended on 11 November 2013. Several global gravity field models have been developed from GOCE data. The development of GOCE-based global gravity models has been achieved mainly by three strategies; direct solution (DIR), space-wise approach (SPW) and time-wise solution (TIM). In addition, to the three ESA's solutions mentioned, models based on a combination of GOCE data and other satellite only data sets have also been developed and are referred to as combined satellite field model (GOCO). GOCE-based GGMs developed until the end of the mission include: DIR (releases 1, 2, 3, 4, and 5), TIM (releases 1, 2, 3, 4 and 5), SPW (releases 1, 2 and 4) and GOCO (releases 1, 2, 3 and 5). It should be noted that SPW (releases 3 and 5) and GOCO (release 4) are missing because they were not processed, hence not included in the current study.

GOCE-based GGMs have been evaluated in different parts of the world by several authors (e.g. Gruber et al. 2011; Janák and Pitoňák 2011; Hirt et al. 2011; Guimarães et al. 2012; Odera and Fukuda 2013, Yi et al. 2013; Yi and Rummel 2014; Abd-Elmotaal 2015; Cheng and Ries 2015; Godah et al. 2015; Hirt et al. 2015; Huang and Véronneau 2015). The GOCE mission aimed at providing the geoid and gravity anomalies with an uncertainty of 1–2 cm and

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1 mGal, respectively, both at a resolution of 100 km, corresponding to spherical harmonic degree and order 200 (e.g. Pail et al. 2011). Precise geoid modelling is the first important step towards establishment of a geoid-based height system. Although new techniques for gravimetric geoid determination have been advanced in the last two decades or slightly more, e.g. remove–compute–restore (Schwarz et al. 1990) and least square modification of Stokes's formula (Sjöberg, 2003), much of the improvements in long-wavelength geoid information required in these techniques have been due to the contribution of recent dedicated satellite gravity missions [e.g. Gravity Recovery and Climate Experiment (GRACE), Challenging Mini-satellite Payload (CHAMP) and Gravity field and steady-state Ocean Circulation Explorer (GOCE)].

Odera and Fukuda (2013) investigated the contribution of the first released GOCE-based GGMs (DIR 1, 2, 3; TIM 1, 2, 3, SPW 1, 2 and GOCO 1, 2) in improvements of geoid model in the long-wavelength components over Japan. The results showed that GOCE-based models could improve geoid model in Shikoku area only. In the current study, we carry out evaluation of GOCE-based models covering the entire GOCE mission using terrestrial free-air gravity anomalies and geometric geoid undulations over Japan. Further evaluations are carried out over each of the four main Japanese islands of Hokkaido, Honshu, Shikoku and Kyushu. Honshu Island is divided into three parts (north Honshu, central Honshu and west Honshu) due to its size and geometry.

## Methods

Seventeen GOCE-based GGMs have been considered in the current evaluations (Table 1). Earth gravitational model of 2008 (EGM2008) is also included for comparative analysis. The assessment is based on geometric geoid undulations, obtained from 816 GPS/levelling points and free-air gravity anomalies, obtained from 6951 first-order gravity points over Japan. The data were provided by the Geospatial Information Authority of Japan (http://www.gsi.go.jp/cais/space-index-e.html). The approximate accuracy of GPS coordinates is $\pm 1$ cm horizontally and $\pm 2$ cm vertically. The maximum allowable accuracy of levelling data is approximated by $15\sqrt{K}$ mm, where $K$ is the levelling distance in km. The accuracy of gravity data is $\pm 1$ mGal. Figure 1 shows the distribution of GPS/levelling and first-order gravity data over the four main islands of Japan. The number of GPS/levelling data points over the six sub-regions is: 163 for Hokkaido, 171 for north Honshu, 163 for central Honshu, 158 for west Honshu, 56 for Shikoku and 105 for Kyushu. The number of gravity data points over the six sub-regions are; 1431 for Hokkaido, 1368 for north Honshu, 1620 for central Honshu, 1166 for west Honshu, 401 for Shikoku and 965 for Kyushu. Although the Geospatial Information Authority of Japan has acquired a new set of GPS/levelling data at 971 points (Miyahara et al. 2014), including initially released 816 points used in this study, we do not expect significant differences in the common points. Also, such data sets were not available for the current research.

**Table 1 GOCE-based GGMs evaluated in this study (yrs. mean years)**

| Model | $n_{max.}$ | Data | References |
|---|---|---|---|
| TIM1 | 224 | GOCE (2 months) | Pail et al. (2010a) |
| TIM2 | 250 | GOCE (8 months) | Pail et al. (2011) |
| TIM3 | 250 | GOCE (12 months) | Pail et al. (2011) |
| TIM4 | 250 | GOCE (26.5 months) | Pail et al. (2011) |
| TIM5 | 280 | GOCE (42 months) | Brockmann et al. (2014) |
| DIR1 | 240 | GOCE (2 months), GRACE (7.5 yrs.), LAGEOS (7 yrs.) | Bruinsma et al. (2010) |
| DIR2 | 240 | GOCE (8 months), GRACE (7.5 yrs.), LAGEOS (7 yrs.) | Bruinsma et al. (2010) |
| DIR3 | 240 | GOCE (12 months), GRACE (7 yrs.), LAGEOS (7 yrs.) | Bruinsma et al. (2010) |
| DIR4 | 240 | GOCE (28 months), GRACE (7 yrs.), LAGEOS (25 yrs.) | Bruinsma et al. (2013) |
| DIR5 | 300 | GOCE (42 months), GRACE (10 yrs.), LAGEOS (25 yrs.) | Bruinsma et al. (2013) |
| GOCO01S | 224 | GOCE (2 months), GRACE (7.5 yrs.) | Pail et al. (2010b) |
| GOCO02S | 250 | GOCE (8 months), GRACE (7.5 yrs.), CHAMP (8 yrs.), SLR (5 yrs.) | Goiginger et al. (2011) |
| GOCO03S | 250 | GOCE (18 months), GRACE (7.5 yrs.), CHAMP (8 yrs.), SLR (5 yrs.) | Mayer-Gürr et al. (2012) |
| GOCO05S | 280 | GOCE (42 months), GRACE (10.5 yrs.), CHAMP (8 yrs.), SLR (5 yrs.) | Mayer-Gürr et al. (2015) |
| SPW1 | 210 | GOCE (2 months), EGM2008 as background model | Migliaccio et al. (2010) |
| SPW2 | 240 | GOCE (8 months), EGM2008 as background model | Migliaccio et al. (2011) |
| SPW4 | 280 | GOCE (33 months), EGM2008 as background model | Gatti et al. (2014) |
| EGM2008 | 2159 | GRACE, terrestrial gravity and altimetric data | Pavlis et al. (2012) |

EGM2008 is also included

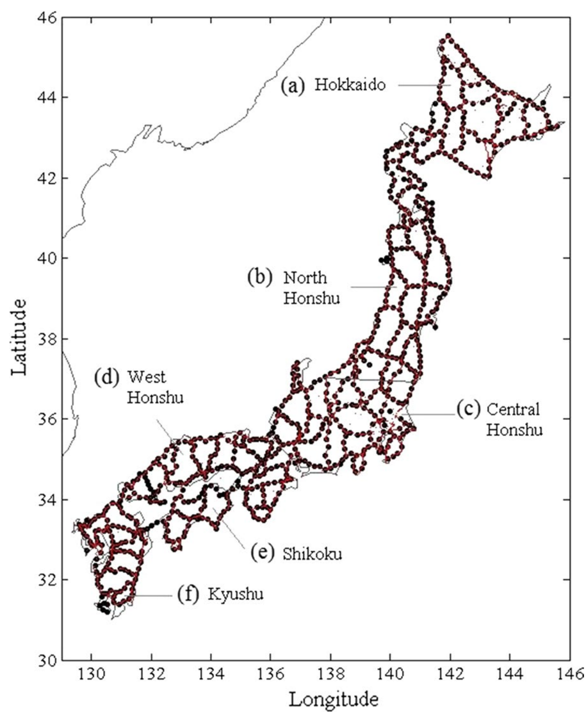


**Fig. 1** Distribution of GPS/levelling (big black dots) and first-order gravity (small red dots) data over the four main islands (adapted from Odera and Fukuda 2013)

The evaluation of GOCE-based GGMs is carried out in two ways. The first method determines standard deviation of the differences between free-air gravity anomalies (obtained from observed gravity data in Japan) and free-air gravity anomalies implied by GOCE-based GGMs. The second method determines standard deviation of the differences between GPS/levelling geoid undulations (obtained from observed GPS and precise levelling data in Japan) and geoid undulations implied by GOCE-based GGMs. The free-air gravity anomalies and geoid undulations implied by GOCE-based GGMs are computed at intervals of degree 30 starting from 150 up to 270 spherical harmonic degrees. This is because all the GGMs considered perform practically at the same level for the wavelengths longer than degree 150.

The geoid undulation and free-air gravity anomaly implied by a GGM are generally obtained by Eqs. 1 and 2, respectively.

$$N_{\mathrm{GGM}} = N_o + C_T + \frac{GM}{r\gamma}\sum_{n=2}^{n\max}\left(\frac{a_{\mathrm{ref}}}{r}\right)^n \sum_{m=0}^{n}(\bar{C}^*_{nm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda)\bar{P}_{nm}(\cos\theta), \quad (1)$$

$$\Delta g_{\mathrm{GGM}} = \Delta g_o + \frac{GM}{r^2}\sum_{n=2}^{n\max}\left(\frac{a_{\mathrm{ref}}}{r}\right)^n (n-1)\sum_{m=0}^{n}(\bar{C}^*_{nm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda)\bar{P}_{nm}(\cos\theta), \quad (2)$$

where $N_o$ and $\Delta g_o$ are zero-order degree terms for geoid undulation and gravity anomaly, respectively, $C_T$ is a conversion term used to convert height anomaly to geoid undulation, $GM$ is the product of the universal gravitational constant and mass of the Earth, $a_{\mathrm{ref}}$ is a scaling parameter associated with a particular GGM, $\bar{P}_{nm}(\cos\theta)$ are fully normalised associated Legendre functions for degree $n$ and order $m$, $\bar{C}^*_{nm}$ and $\bar{S}_{nm}$ are fully normalised spherical harmonic coefficients after reduction by the even zonal harmonics of the reference ellipsoid, and $n_{\max}$ is the finite maximum degree of a GGM.

## Results

The statistics of the differences between observed and GOCE-based GGMs implied gravity anomalies in Japan, and the six sub-regions are presented in Fig. 2. Consequently, the statistics of the differences between observed and GOCE-based GGMs implied geoid undulations in Japan and the six sub-regions are presented in Fig. 3. Corresponding results for EGM2008 are also included for comparative analysis. The models are truncated at 150, 180, 210, 240 and 270 spherical harmonic degrees, where the maximum degrees for each model allow.

It is observed that the performance of GOCE-based GGMs over Japan is practically the same at degree 150 for both free-air gravity anomalies (Fig. 2) and geoid undulations (Fig. 3). They also perform at the same level with EGM2008, although some GOCE-based GGMs perform slightly better than EGM2008 at degree 150 for geoid undulations (SPW1, 2, DIR1, TIM2) and gravity anomalies (GOCO1, 2, 3). The latest GOCE GGMs (releases 4 and 5) do not improve the performance over the earlier released GGMs (releases 1, 2, 3) in Japan at degree 150. Similar patterns are noted over the six sub-regions of Hokkaido, north Honshu, central Honshu, west Honshu, Shikoku and Kyushu.

There is a slight difference in the performance of GOCE-based GGMs over Japan (only 0.2 mGal and 0.8 cm for gravity anomalies and geoid undulations, respectively) at 180 spherical harmonic degrees. EGM2008 performs slightly better than GOCE-based GGMs over Japan at degree 180. However, gravity anomalies comparisons show that SPW4 and DIR4 perform at the same level with EGM2008 in Kyushu, while GOCO2, TIM2 and DIR2 interestingly perform better than EGM2008 in west Honshu and most GOCE-based

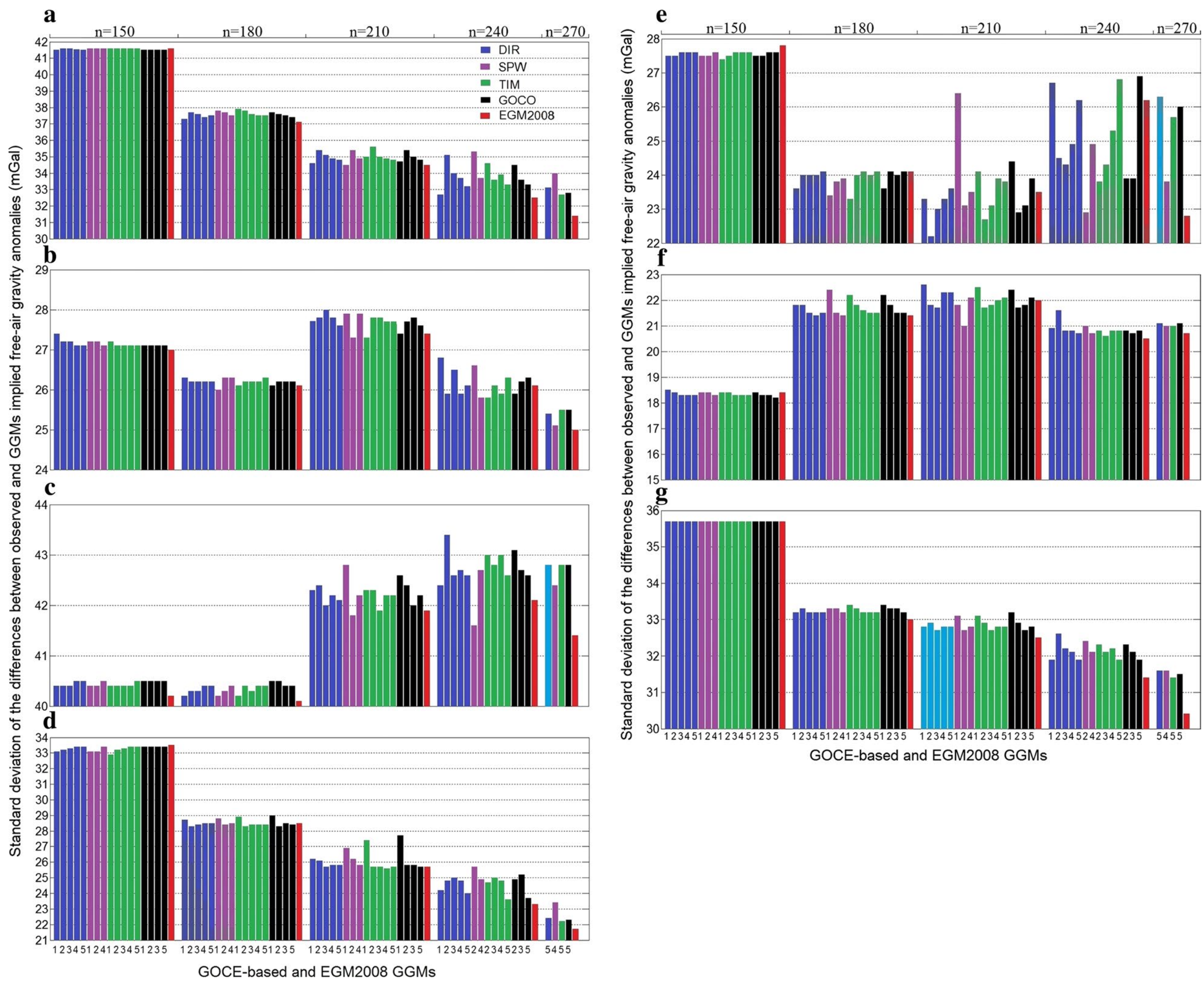


**Fig. 2** Standard deviations of the differences between observed and GGMs implied free-air gravity anomalies over—**a** Hokkaido, **b** north Honshu, **c** central Honshu, **d** west Honshu, **e** Shikoku, **f** Kyushu and **g** Japan. **n** represents the spherical harmonic degrees

GGMs perform better than EGM2008 in Shikoku at degree 180. On the other hand, geoid undulations comparisons show that GOCO5 and DIR5 perform slightly better than EGM2008 in north Honshu, while most GOCE-based GGMs perform better than EGM2008 in west Honshu and all GOCE-based GGMs perform better than EGM2008 in Shikoku at degree 180. Generally, the latest GOCE-based GGMs (releases 4 and 5) improve the performance over the first GGMs (releases 1, 2 and 3) at 180 and higher degrees over Japan. Although some surprises are also noted where early releases of GOCE-based GGMs perform better than the latest releases, such surprises are extremely minimal with time-wise solution (TIM). This indicates a good consistency in the GOCE data. It also indicates that more data collected by GOCE in the last months of operation have improved the performance of GOCE-based GGMs in the long-to-medium wavelength components.

Comparisons at degrees 210–270 show that EGM2008 performs better than GOCE-based GGMs over Japan. Although gravity anomalies show that some GOCE-based GGMs perform slightly better than EGM2008 between degrees 210 and 240 in north Honshu, central Honshu, west Honshu, Shikoku and Kyushu, independent check by geoid undulations show that GOCE GGMs perform better than EGM2008 only in Shikoku (at degree 210, best models are DIR5, TIM5 and GOCO5 and at degree 240, best models are DIR4 and SPW4) and west Honshu (at degree 210, best models are TIM5, TIM4 and GOCO5). The best models referred to here perform practically at the same level. EGM2008 performs better than GOCE-based GGMs over Japan

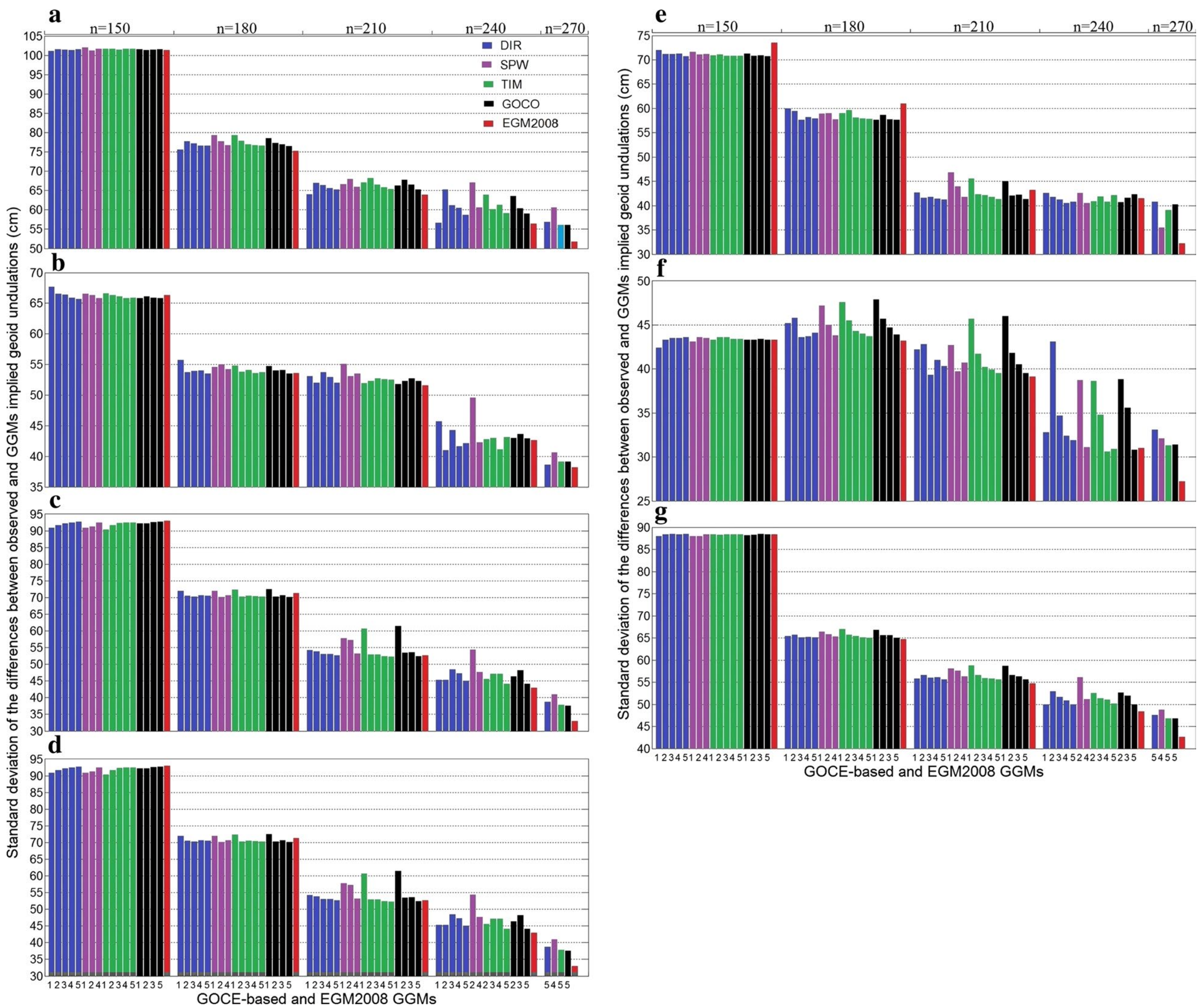


**Fig. 3** Standard deviations of the differences between observed and GGMs implied geoid undulations over—**a** Hokkaido, **b** north Honshu, **c** central Honshu, **d** west Honshu, **e** Shikoku, **f** Kyushu and **g** Japan. **n** represents the spherical harmonic degrees

and all the six sub-regions at 270 spherical harmonic degrees. TIM5 performs better than other GOCE-based GGMs over Japan at degree 270 when both geoid undulations and gravity anomalies are considered.

At the end of GOCE mission, GOCE-based GGMs now perform better than EGM2008 in north Honshu (up to degree 180), west Honshu (up to degree 210) and Shikoku (up to degree 240). GOCE-based GGMs can now significantly improve geoid model in Japan if combined with EGM2008 to cater for the omission errors in the medium-to-short wavelength components over the three sub-regions in Japan. This is approximately half of the area of study in terms of spatial extents. There is no significant evidence of geoid model improvement by GOCE-based GGMs over EGM2008 in Hokkaido, Central Honshu and Kyushu regions. It is noted that all GGMs evaluated perform poorly in the mountainous area of central Honshu, for gravity anomalies (Fig. 2c) beyond degree 180. This indicates a general decline in the accuracy of GGMs in the medium-to-short wavelength components in mountainous areas. However, the trend is not replicated in the geoid undulation differences (Fig. 3c) because most GPS/levelling data have low elevations (<1000 m) even in mountainous areas like central Honshu (e.g. Odera and Fukuda 2015). It is also noted that GOCE GGMs perform relatively better in Kyushu (considering the magnitude of standard deviation) than other regions over Japan (Figs. 2f, 3f). This may be attributed to the fact that Kyushu Island is in a relatively lower elevation terrain than the other regions considered in the current study.

## Conclusions

This study represents a comprehensive assessment of GOCE data and possible contribution of GOCE GGMs in geoid modelling over Japan covering the entire GOCE mission. Seventeen GOCE-based GGMs (releases 1, 2, 3, 4 and 5) have been evaluated over Japan using gravity anomalies (from first-order gravity data) and geoid undulations (from GPS/levelling data) at 150, 180, 210, 240 and 270 spherical harmonic degrees. A general consistency in GOCE data is observed in the increasing accuracy with increase in length of observations. The latest GGMs (releases 4 and 5) perform better than the earlier released GGMs (releases 1, 2 and 3) but only after 150 spherical harmonic degrees. All the GOCE-based GGMs evaluated and EGM2008 perform practically at the same level at degree 150 over Japan. Improvement of geoid model over Japan by GOCE GGMs is evident in north Honshu (up to degree 180), west Honshu (up to degree 210) and Shikoku (up to degree 240), with significant improvement at degree 180. EGM2008 performs better than GOCE-based GGMs in Hokkaido, Central Honshu and Kyushu over the same range of spherical harmonic degrees. Following possibilities of further improvement of the geoid model over approximately half of Japan by GOCE data, we intend to develop a more improved geoid model for Japan based on GOCE data (in north Honshu, west Honshu and Shikoku), EGM2008 and terrestrial gravity data using the method described in Odera and Fukuda (2014).

### Abbreviations

CHAMP: Challenging Mini-satellite Payload; DIR: direct solution; EGM2008: earth gravitational model of 2008; ESA: European Space Agency; GGM: global gravity model; GOCE: Gravity field and steady-state Ocean Circulation Explorer; GOCO: combined satellite field model; GPS: Global Positioning System; GRACE: Gravity Recovery and Climate Experiment; LAGEOS: Laser Geodynamics Satellite; SLR: satellite laser ranging; SPW: space-wise approach; TIM: time-wise solution.

### Authors' contributions

PAO and YF designed the research, and YF facilitated the data acquisition and interpretation. PAO carried out the computations and related analyses. He also wrote and revised the paper. Both authors read and approved the final manuscript.

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### Competing interests

The authors declare that they have no competing interests.

### Availability of data and materials

The GPS/levelling and gravity data used in this study can be obtained from the Geospatial Information Authority of Japan. The GGMs in form of spherical coefficients are freely available at the International Centre for Global Gravity Field Models website (http://icgem.gfz-potsdam.de/ICGEM/).

### Consent for publication

Not applicable.

### Ethics approval and consent to participate

Not applicable.

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